HAZARD MAPPING AS PART OF CIVIL DEFENCE PREVENTIVE & CONTINGENCY ACTIONS: A CASE STUDY FROM DIADEMA, BRAZIL

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Abstract: In the State of São Paulo, south east Brazil, public authorities, at both municipal and state administrative levels, are formally required to work together to tackle natural hazards such as landsliding and flooding. Possible responses include various preventive and contingency actions in which hazard mapping plays a key role.

This paper describes a hazard zonation exercise based on the combined use of high-resolution satellite imagery (Ikonos sensor) and ground checks to provide civil defence authorities and decision-makers with information about land occupation and ground conditions as well as technical advice on the severity of potential instability, likelihood of hazard, and potential mitigating and remedial measures.

Driving aspects considered for the approach used to do this include the need to produce outcomes in an updateable and reliable manner, and in suitable formats to be conveyed to non-specialists.

Risk zones are firstly identified through site visits and according to observed terrain characteristics (e.g. declivity, soil weathering profile) and evidence of geodynamic processes (e.g. landslide scars, riverbank erosion). Satellite images are used to assist with the identification of buildings and houses liable to be affected and the delineation of risk zone boundaries.

A qualitative ranking scheme uses four levels of risk: R1 (low); R2 (moderate); R3 (high); R4 (very-high). The low risk (R1) zone includes only predisposing factors to instability (e.g. informal housing and cuttings in steep slope areas) or to flooding (e.g. informal housing in lowland areas and close to watercourses but no reported flood within the last 5 years). The very-high risk (R4) zone is characterized by significant evidence of instability (e.g. presence of cracks in soil and walls, formation of subsidence steps) or flooding (e.g. dense occupation of the riverside and at least 3 severe floods reported within the last 5 years).

In the municipality of Diadema, 46 hazardous areas were identified (19 relating to landsliding, 22 to flooding, 5 to both phenomena). Within these areas 18 zones were ranked as R4, 33 as R3, 30 as R2, and 17 as R1.

Résumé: Les autorités publiques de l'Etat de São Paulo (Sudest Brésil), travaillent en coopération avec les mairies pour prévenir les risques posés par les phenomènes d'éboulements et d'innondations. La cartographie des zones exposées à ces risques est un outil trés important car peut offrir les réponses possibles aux moyens préventifs ou de contingence.

Ce travail décrit l'utilisation combinée des images de satellite à haute-résolution (capteur Ikonos) avec des vérifications rapides du terrain pour fournir aux autorités de Défense Civile et décisionnaires des informations sur l'occupation du sol et sur ses conditions geotéchniques. Ces informations permettent d'estimer la sévérité des procès d'instabilité et la probabilité d'occurrence de ces phenomènes, ce qui a permi d'adopter les actions pour mitiger et remédier les situations des risques.

La necessité d'interpréter ces informations et de produire des resultáts confiables d'une façon rapide, dans des formats qui soient convenables pour des non-specialistes, est l'aspect principal de ce travail.

Les zones exposées aux risques sont identifiées, premièrement, par le séjour aux endroites à fin de connaître les caractéristiques du terrain (ex. déclivité, profil d'intempérisation du sol etc.) et vérifier des traits geodynamiques.

Les images de satellite sont utilisées pour idéntifier les immeubles et les habitations sensibles aux hazards geotécniques et pour délimiter les zones de risque. Une classification qualitative des risques a été formulée en quatre niveaux: R1 (bas), R2 (modéré), R3 (haut), et R4 (très haut). Le zone de risque R1 comporte seulement les facteurs qui predisposent l'instabilité ou l'innondation (ex. l'occupation indistinct ou terrassement aux pentes très inclinées). Le zone de risque R4 est caractérisée par l'évidence significative d'instabilité ou d'innondation (e.x. la presénce des fendres au sol et aux murs, la formation de degrés de subsidence, haute densité d'occupation aux parties basses, et la présence de trois phenomènes d'inondations sévères dans un intervale de 5 anées).

À la ville de Diadema, banlieue de la métropole de São Paulo, existent 46 lieux environementallement dangereux: 19 par éboulement, 22 par innondation, et 5 par les deux phenomènes ensemble, 18 zones des risques ont été rangées comme R4, 33 comme R3, 30 comme R2, et 17 comme R1.

Keywords: geological hazards, landslides, floods, land use, environmental urban, engineering geology maps.

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INTRODUCTION

In the last 20 years, landsliding and flooding hazards have been affecting an increasing geographical area of in the State of Sao Paulo, Brazil, thus increasing the damage caused to people and properties. In part this is due to high rates of population growth in association with poorly planned/unplanned land occupation, the concentration of dwellings in unsuitable areas and inattention to environmental management. This increases the exposure of the community to risk and increases the impact of hazard events.

To deal with this situation, Civil Defence Preventive and Contingency Programmes are being implemented. The first programmes were introduced in the 1980's to tackle a number of disasters that caused many casualties and much damage to the Cubatão Industrial Estate on the steep slopes of the Serra do Mar Ridge at Cubatão and Santos cities. The assessment of processes giving rise to hazards and risk analysis play a key role in these programmes. The current research work is part of an agreement between the Geological Institute and the State Civil Defence Office, the purpose of which is to provide technical assistance with the identification and management of risks associated with landslides and floods in residential and urban areas. The entire project covered six cities of the State of Sao Paulo, including the municipality of Diadema, which is the focus of this paper.

Diadema is a small city of only 31.8 km^2 situated in the Metropolitan Region of Sao Paulo (Figure 1). Its population reached 383,629 inhabitants in 2004 showing a three-fold increase in the 30 years since 1974 when the population was 119,327 inhabitants (SEADE 2005). At around 12,000 people per km^2, the population density is one of the highest of the State of Sao Paulo, in which the overall average is 156 inhabitant/km^2 for urban and non-urban areas.

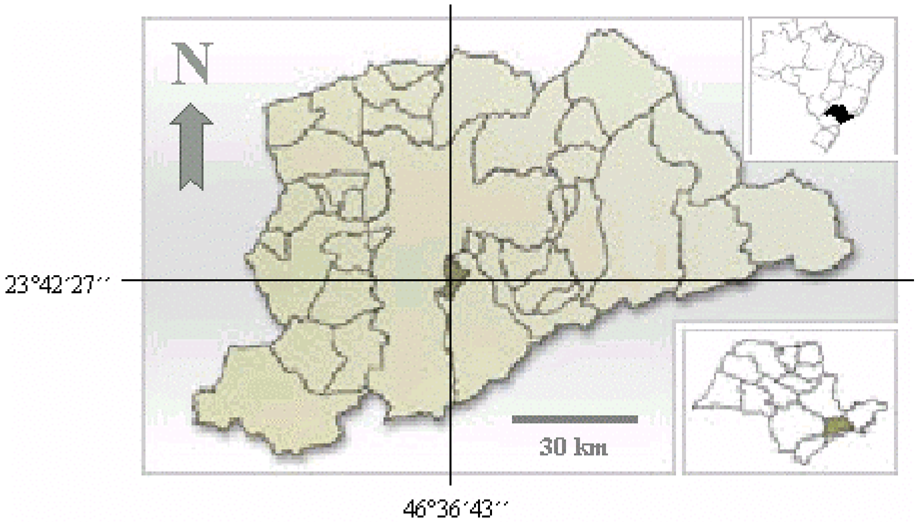

Figure 1. Location of Diadema City in the Metropolitan District of São Paulo.

The regional geology setting consists of Pre-Cambrian metasedimentary rocks of the Embu Complex (micaschists and biotite-muscovite gneisses), which are bound by shear zones to the north and south, and also by intrusive granites and Tertiary and Quaternary sediments (Coutinho 1972). The geomorphological setting comprises the Atlantic Plateau, locally formed of elongated hills with sharp convex tops, and small-hills with flat to convex tops, flat ramps and alluvial plains. The altitude ranges between 720 and 860 m and the slope steepness varies from 0 to 40° (Almeida 1964, Ponçano 1981, Ross & Moroz 1997).

This paper describes hazard mapping and risk zoning applied to housing and urban areas. It was based on a qualitative ranking scheme with four levels of risk: R1 (low); R2 (moderate); R3 (high); R4 (very-high). The concepts of risk used in this work accord with the United Nations (2002) definition which states that risk results from interactions between natural or human induced hazards and vulnerable conditions. Thus, a quantitative assessment of risk, R, can be derived from the hazard likelihood of occurrence, H, multiplied by the vulnerability, V; so $R = H \times V$.

The methods combine the use of high-resolution satellite imagery (Ikonos sensor) and ortho-rectified aerial photographs with ground checks, to provide civil defence authorities and decision-makers with information about land occupation and ground conditions as well as technical advice on the severity of potential instability, likelihood of hazard, and potential mitigating and possible remedial measures. Driving factors include the need to produce outcomes in an updateable and reliable manner, and in suitable formats to be conveyed to non-specialists.

METHODS

The methods consisted of the production of an inventory of landsliding and flooding events, processing and interpretation of high-resolution images, fieldwork and GIS-based spatial analyses. Figure 2 shows the methodology framework used in the study, which was of six months duration.

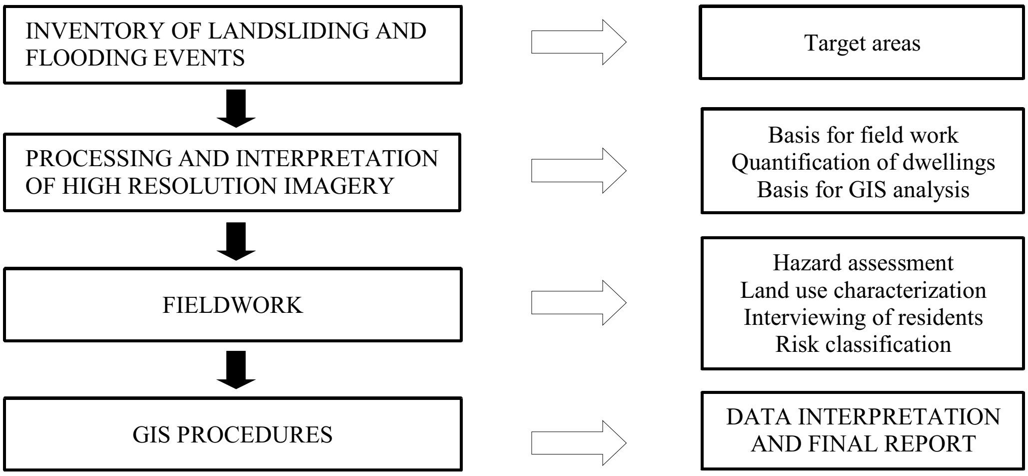

Figure 2. Methodology framework used in the study.

Inventory of landsliding and flooding events

Taking into account the short period of time available to complete the project, a detailed survey of previous events and hazard mapping concentrated on 53 target areas. These areas were selected from a database provided by the Local Civil Defence Authority that listed 132 records of landslides and floods that occurred between January 1998 and March 2004. The 53 areas were displayed on a 1:7,000 topographic map, also provided by the Local Civil Defence Authority.

Processing and interpretation of high resolution imagery

Two types of images were utilized: a) digital aerial photographs taken in 2000, and b) Ikonos satellite images taken in 2002, both of them ortho-rectified. The spatial resolution of the images was about 1 m and although both were of similar nominal resolution, the aerial photographs showed a little better visualization. Hardcopies of the digital images printed at an approximate scale of 1:3,000, were utilized during fieldwork for hazard characterization and risk zone delimitation. Digital outputs were transferred to SPRING GIS package for land use characterization and to determine the number of dwellings present in each risk zone.

Fieldwork

The fieldwork, which was carried out between September and December 2004, comprised a geological-geotechnical survey for hazard characterization at local and outcrop scale, land use characterization, interviews with local populations, and risk classification. The data were systematically recorded on evaluation forms, as proposed by Macedo *et al.* (2004a). Local Civil Defence Office staff supported the fieldwork operations with logistic support and by supplying key additional information about target areas and hazard events.

Geological-geotechnical survey for hazard characterization

The expedite geological-geotechnical survey included description and assessment of local geomorphological features, including ground declivity and surfacing, geodynamic processes such as landslides and erosion, perpetual water courses, streams and alluvial plains, as well as floodpaths and locations of erosional undercutting of riverbanks. The data collected varied according to its location on hill-slopes and alluvial plains.

Housing located on the hill slopes is potentially subject to gravitational mass movements controlled by declivity, type of material involved (soil, rocks, superficial deposits, fill etc), type and rate of movement, (debris flow, rotational or planar mass failure), slope geometry, type of slope (natural, cut or fill), position of the movement with respect to slope (near crest, mid-slope, near toe), groundwater conditions and surface water flows (Besio *et al.* 1998, Fernandes *et al.* 2004, Tominaga *et al.* 2004).

Housing on alluvial plains is subject to flooding, undercutting and erosion and the deposition of the material carried by floodwaters. In urban areas, the geometry of watercourses tends to be highly modified by human activities. Channelling and straightening of the streambed usually change the balance of the processes of erosion and sedimentation, possibly giving unexpected results. Partial infilling of water channels and low-lying areas, waste disposal and increased run-off in urban areas increases the amount of water being carried.

The factors of importance to assess hazards to housing situated on alluvial plains included the channel typology (natural, straight, sinuous, man-modified), distance between house and the channel edge, height of the channel slope, level of the floods and features such as cracking of walls and floors and riverbank erosion (Cerri & Carvalho 1990).

Land use characterization

The criteria observed during the fieldwork were: mode of construction (wood or brickwork, with or without concrete frames), quantity of construction, number of inhabitants (estimated through the number of dwellings) and evidence of active ground movements, such as cracks and distortion in walls or floors. Also noted was the location in relation to hill slopes, watercourses and potential flood routes as well as features such as landslides scars, steep slopes and erosion and deposition of debris. Any evidence of past flood levels, such as tide marks and people's recollections, were also recorded, as well as the position in relation to hill-slopes or riverbanks.

Interviewing of residents

An important contribution to the data collected was given by orally by local people. For each risk zone at least one or two inhabitants were interviewed. The main questions related to the occurrence of previous hazard events in terms of the periodicity, magnitude and the effects, as well as the evidence for new problems. Such data gathering by talking with inhabitants is an unusual aspect of this fieldwork but it provided much relevant information about the relative vulnerability of the population and, to some extent, guided approaches for possible mitigation measures.

Risk classification

The risk zonation was carried out in the field, taking into account data from the geological-geotechnical survey, land use, oral information, Local Civil Defence Authority data and high-resolution satellite images. A qualitative ranking scheme using four levels of risk: R1 (low); R2 (moderate); R3 (high); R4 (very-high) was employed in accordance with the concept of risk presented by United Nations (2002): R = H x V, where:

R (risk) - the probability of harmful consequences or losses. These may involve loss of life, injury to people, damage or disruption to property, the environment, livelihood or economic activity resulting from interactions between natural or human induced hazards and vulnerable conditions.

H (hazard) - a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.

V (vulnerability) – the condition and processes resulting from physical, social, economical and environmental factors which increase the susceptibility of potential recipient to the impact of a particular hazard.

Table 1 shows the criteria employed for risk classification based in Macedo *et al.* (2004b). A qualitative approach was taken in which the surveyor assessed the constraints on and evidences for a hazardous situation compared them with a set of standard situations, to ascribe an appropriate classification.

Table 1. General criteria and description of the risk classification.

RISK	DESCRIPTION
R1-Low	Local geological-geotechnical factors (e.g. topography, slope steepness, soil type etc) do not favour or predispose development of geodynamic hazardous processes (landsliding, undercutting, flooding). No evidence of slope or riverbank instability, or stream overflow. Absent or scarce previous record of instability and/or flooding events. Occurrence of damaging events unlikely (probability < 10 %) within following 12 months provided current observed conditions are kept.
R2-Mode-rate	Local geological-geotechnical factors (e.g. topography, slope steepness, soil type etc) and man-made interventions moderately favour or predispose development of geodynamic hazardous processes (landsliding, undercutting, flooding). Some minor features (little evidence) of land instability and/or stream overflow observed. Scattered records of landsliding and flooding events over recent years. Moderate probability (10–50 %) of occurrence of damaging events within following 12 months in case of severe and prolonged rainfall periods.
R3-High	Local geological-geotechnical factors (e.g. topography, slope steepness, soil type etc) and man-made interventions highly favour or predispose development of geodynamic hazardous processes (landsliding, undercutting, flooding). Presence of significant features of land instability (cracks in soil and rock mass, subsidence patches etc) and/or stream overflow (water marks on walls, riverbank erosion etc). In some cases geodynamic hazardous processes are still active and can be monitored. Relatively frequent records of landsliding and flooding events over recent years. High probability (50–80 %) of occurrence of damaging events within following 12 months in case of severe and prolonged rainfall periods.
R4-Very High	Local geological-geotechnical factors (e.g. topography, slope steepness, soil type) and man-made interventions highly favour or predispose development of geodynamic hazardous processes (landsliding, undercutting, flooding). Presence of large number of features of land instability (cracks in structures such as walls, in soil and rock mass, leaning of trees and electric paws, erosion rills and ravines, landslide scars, subsidence patches in cuttings etc) and/or stream overflow (water marks on walls, riverbank erosion, proximity of dwellings to riverbank etc). In most cases, critical conditions are observed with advanced geodynamic hazardous processes in course, thus requiring immediate remedial and/or contingency actions. Frequent records of landsliding and flooding events over recent years. Very high probability (> 80 %) of occurrence of damaging events within following 12 months in case of severe and prolonged rainfall periods.

GIS procedures

Cartographic and thematic information were handled and processed using SPRING software (Camara *et al.* 1996), a freeware GIS and image processing package, developed by INPE (Brazilian Institute for Aerospatial Research). The operations performed included: a) importation of topographic maps from DXF format and conversion into pertinent formats; b) processing and analysis of satellite images, and c) digitising of field data and integration with ancillary data for production of risk zoning map.

RESULTS

The studies were carried out over 56 target areas, 53 arose from the inventory of the events and three news ones were added during fieldwork. Among them, 46 areas were classified as under some risk and were divided into 98 sectors in respect to the type of processes, hazard and housing vulnerability. In 10 areas the remediation works had been carried out and there was insufficient evidence to include them in present risk classification. Curiously, one of the areas was located out of the boundaries of the city. Therefore the local population formally belonged to Sao Paulo city, although in many aspects such as infrastructure and health services, electoral territory and Civil Defence support, it is managed by Diadema. Figure 3 shows the distribution of the risk zones over the studied area.

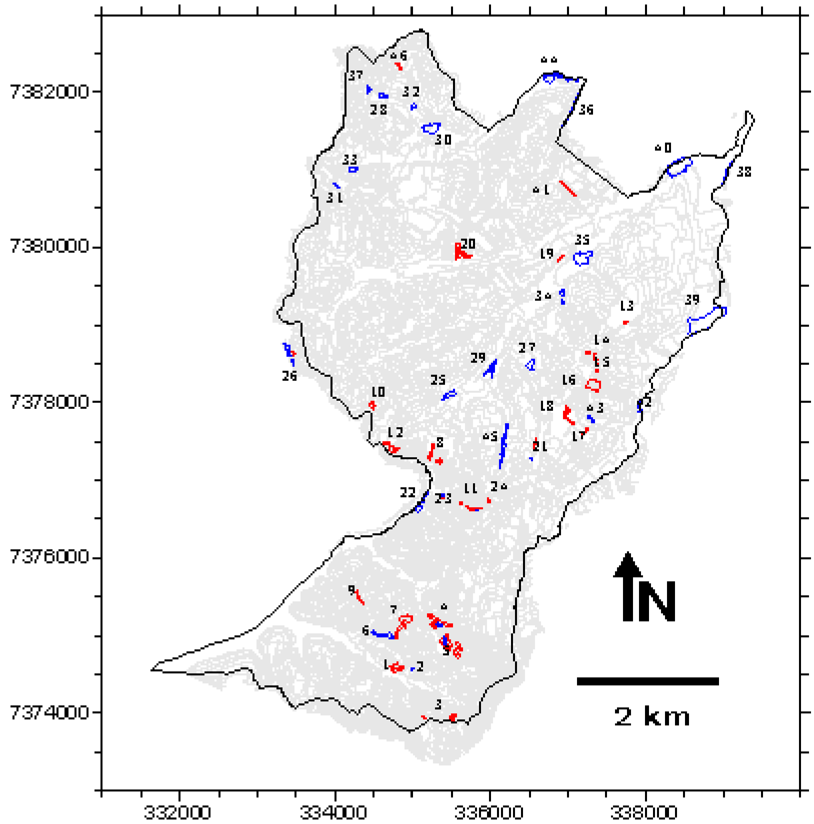

Figure 3. Distribution of the 46 risk areas over the municipality of Diadema. Blue: flooding and river undercutting hazards; red: landsliding hazards.

Geology and Geomorphology constraints

The risk areas are distributed all over Diadema's territory, which constitutes many lithologies and relief forms (Figures 4 and 5). In the south, where schists are the main lithology, the drainage density is higher and the hills have sharp tops. In the central and northern zones, Tertiary sedimentary deposits predominate, giving flat-topped hills. Otherwise the slopes formed in this lithology experience more frequent instability than slopes in residual soils derived from metamorphic and igneous rocks. Probably, the greater instability is due to the less cohesive nature of the former deposits, as well as the fact that failures occur due to the unconformity between the sedimentary deposits and underlying metamorphic and igneous basement. On areas of granite outcrop, the amplitude of the hills is greater and the drainage density is smaller. In these areas the main hazards are rock falls and block rolling, which was observed only on this terrain. Due to advanced and homogeneous weathering in the gneiss and migmatite terrains, the main problem was instability of residual soil, as exposed rock and rock blocks were not present.

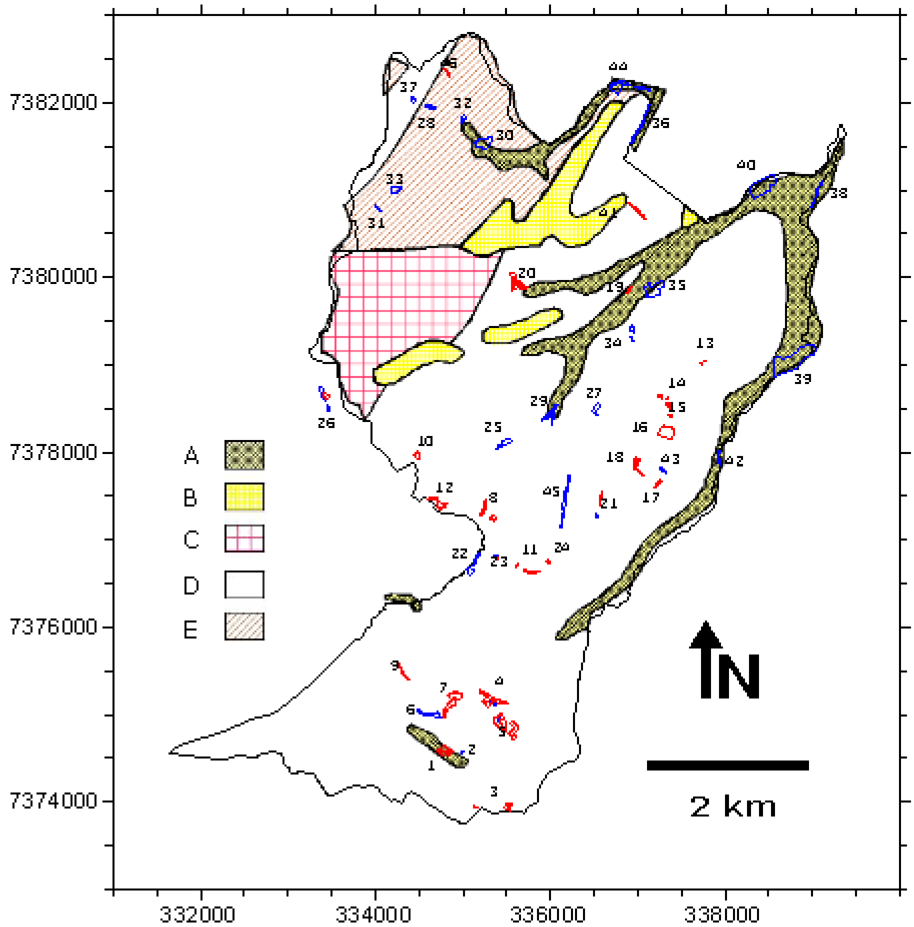

Figure 4. Local geology and distribution of risk areas (from Coutinho 1972). A: Quaternary alluvium; B: Tertiary sedimentary deposits; C: Precambrian granite; D: Precambrian mica-schists; E: Precambrian gneisses. Blue: flooding and river undercutting hazards; red: landsliding hazards.

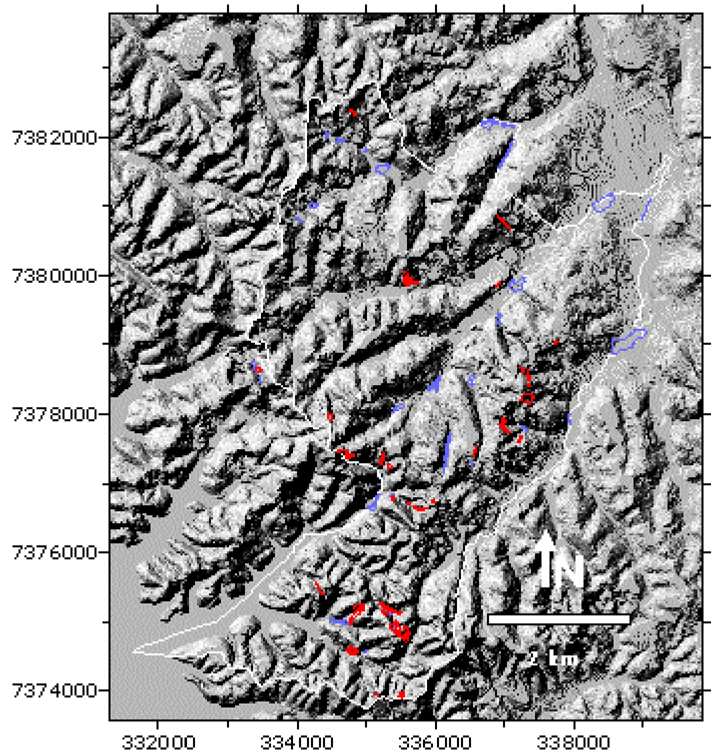

Figure 5. Digital elevation model of Diadema and distribution of risk areas.

Housing vulnerability constraints

Diadema is an intensively developed urban city (see Figures 6 and 7), nevertheless many dwellings suffer from a lack of basic facilities. In general, the central region where most of the areas at risk are situated (see Figure 3) is characterized by high occupation, density and construction of brick buildings (see Figures 8A, 9A and 9C), except for the areas 18 (see Figure 8D), 29 (see Figure 9D) and 45 where wooden houses predominate.

The northwest region shows a medium to high occupation density and better quality brick houses (see Figures 6, 8C). In the northeast of the city most dwellings are classified as low to medium quality brickwork (see Figure 7), except for Area 36 (see Figure 3 and 7) that contains extremely vulnerable wooden houses. In the south, the occupation density is the lowest and the construction material is mostly brick (see Figure 8B), except for the Area 3 where wooden houses predominate.

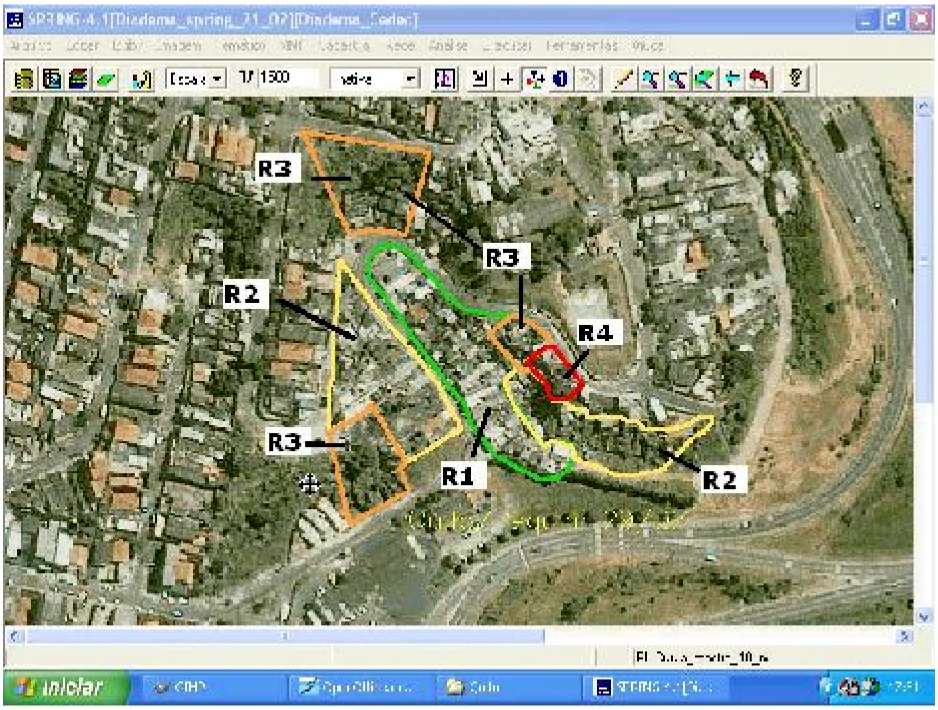

Figure 6. An example of landslide risk zones displayed on an Ikonos satellite image, using SPRING software.

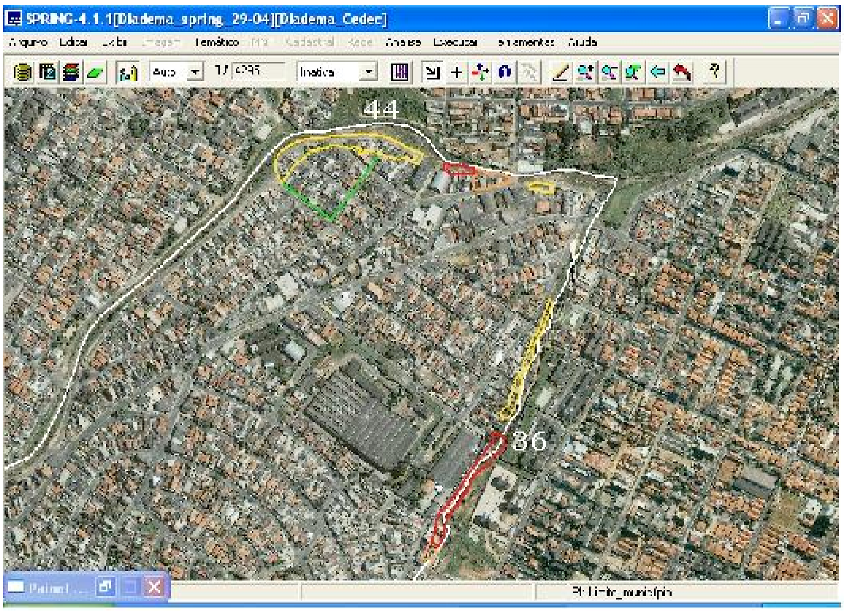

Figure 7. An example of flooding risk zones displayed on Ikonos satellite image, using SPRING software. Green: R1 (low); yellow: R2 (moderate); orange: R3 (high); red: R4 (very high).

Figure 8. Examples of landsliding risk zones. Photographs taken during fieldwork. A- Area 16 – R1 (low); B- Area 5 – R2 (moderate); C- Area 20 – R3 (high); D- Area 18 – R4 (very high).

Figure 9. Examples of flooding risk zones. Photographs taken during fieldwork. A- Area 34 – R1 (low); B- Area 23 – R2 (moderate); C- Area 36 – R3 (high); D- Area 29 – R4 (very high).

Hazard and risk classification

98 sectors were mapped embracing 2,893 houses. 53 zones (embracing 1,285 houses) refer to landsliding, block rolls and tilting and rockfalls hazards whilst 45 to flooding and river undercutting hazards (including 1,608 houses). The zones at risk sum up a total area of 414,030 m^2, which is representative of 1,25% of the total municipality area. The percentage of housing stock at risk can be considered near that value because the house density in Diadema shows little variance. Considering a conservative estimative of four inhabitants each house, there are nearly 12,000 people at risk, which is 3% of the municipal population. Among the risk zones due landsliding hazards, 10 sectors were classified as low risk (comprising 453 houses), 18 as moderate risk (393 houses), 14 as high (308 houses) and 11 as very high risk (131 houses). Figures 6 and 8 show examples of landsliding risk zones, portrayed respectively with Ikonos satellite image and fieldwork photographic records. With regard to risk zones related to flooding hazards, 7 sectors were classified as low risk (embracing 365 houses), 12 as moderate (332 houses), 19 as high (682 houses) and 7 as very high risk (including 229 houses). Figures 7 and 9 display some examples of flooding risk zones, also at Ikonos satellite image and fieldwork photographic records.

As reported above, there was insufficient evidence to classify about 10 target areas. In many cases this due to municipality actions to reduce risk. These included the channelling of streams, other measures to control water flow, and the surfacing of streets, which although increases run-off does control the silting up of watercourses. Retaining walls have also been constructed but in the majority of cases the action has been relocation of residents to other areas, either temporarily or permanently, with the demolition of properties at risk.

DISCUSSION

Land instability and flooding hazards pose considerable threats to residents in many urban areas of the State of São Paulo. In some cases instability involving only a few cubic metres of material had caused loss of life due to the extreme vulnerability of residents in buildings of insubstantial construction. Elsewhere, informal occupation of potentially and actually unstable areas endangers residents and others. State funded mapping work aims to quantify the risks and provide local and State authorities with assessments of the scale, effects and mitigation of instability and flood hazard events, such that appropriate management of the problems and remedial actions can be taken. Research into the use of remotely sensed images, coupled with field studies, has been conducted for hazard assessment and for practical implementations to assist with the formulation of a hazard prediction tool. These have been particular useful in urban areas where different types of hazard, including flooding, slope instability, erosion, and foundation collapse are prevalent.

In Diadema, the vulnerable areas were rapidly drawn directly onto high-resolution satellite images, then analysed and interpreted through desktop studies and during fieldwork. Images have proved to provide more up-to-date geological-geomorphological and land-use information than the large-scale plans available for areas. Furthermore, periodical images taken at different times can be compared, which enables the dating of landform changes and development, as well as rapid changes in land-use, particularly expansion of informal housing.

It would be possible to undertake various engineering works to alleviate potential hazards. However, such solutions are unlikely to be practical given the scale of the problems and the resources of the residents and local authorities. A preventive and contingency approach to allow both populations and authorities to properly cope with hazards and natural phenomena (e.g. severe rainfall) would be of great assistance. At present the surveyor assesses the hazard subjectively whereas there is potential for derivation of hazard rating from a combination of ancillary data and images. Parallel research into image processing is also required, coupled with predictions based on an understanding of the engineering behaviour of the materials in terms of erosion and land instability. Investigations are needed into the geotechnical properties of the materials concerned, including the effects of changes in suction pressures, weathering induced deterioration in strength and the stability of slopes and structures in different conditions. This research would probably need to include laboratory testing and modelling work, to allow calibration of interpretations derived from imagery and facilitate reliable extrapolation of the findings.

CONCLUSIONS

Over the last 30 years, rapid population growth has been taking place in the municipality of Diadema. A significant number of hill slopes and alluvial plains have been occupied, especially for housing, in a rather unplanned and uncontrolled manner. Populations have been increasingly exposed to landsliding and flooding hazards. In part this is due to natural geodynamic processes but the problems are exacerbated by inadequate construction practices, the high vulnerability to damage of insubstantial buildings, poor siting of structures and the developments themselves, particularly the modification of slope profiles and the groundwater and surface water conditions.

Fifty-one zones were classified as being of high and very high risk categories from a total of 98 risk zones mapped throughout the 46 areas. These risky zones encompass approximately 1350 dwellings (R3 and R4 classes) in ground conditions prone to landslides, rockfalls and block tilting, flooding, and riverbank undercutting.

The value of high-resolution satellite images was clearly demonstrated, particularly for accurate delimitation of target areas and risk zones, characterization of land use patterns, and quantification of dwellings. During fieldwork, besides using geological-geotechnical criteria, interviews with local populations has proven to be useful to assist with the characterization of risk zones by providing additional information about previous hazardous events and historical background on land occupation.

In order to tackle risk situations, civil defence preventive and contingency programmes have been set up at regional and local levels in the State of São Paulo, from which the hazard mapping exercise presented here is a key instrument for prioritisation of public authority measures. These may include engineering works such as stream channelling and culverting, slope stabilization, improvements to the drainage and water supply and sewage infrastructure in locations at risk. This is also to include the future construction of housing for low-income populations in safe areas. It was observed that the culverting of streams has been a widespread engineering solution adopted by the local administration, for tackling flooding problems. The indiscriminate use of such measure may be only a relatively short duration solution, as although water throughput is increased this is at the expense of storage capacity and it exacerbates the problems downstream of the scheme. This leads to deterioration in water quality. Apart from these drawbacks it creates the space and even the foundations, for informal land occupation, thus leading to the production of new risks in middle to long-term.

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